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# An Upgrade Plan for FHWA Roadway Safety Simulation Models



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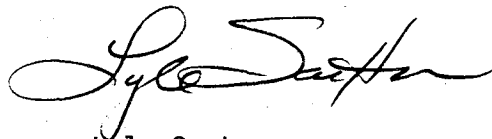
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## FOREWORD

This report (FHWA-RD-93-189) documents a study on the development of a long-range plan for upgrading capabilities and software for simulation of vehicle-barrier response for vehicles impacting roadside safety structures. The existing capabilities and software for vehicle-barrier response simulation and nonlinear finite element analysis were reviewed. This study concluded that the public domain version of the DYNA/NIKE code was preferred for barrier impact analysis.

This report will be of use to researchers interested in evaluating and applying nonlinear finite element analysis software for vehicle impact against barriers, vehicle handling, and barrier failure studies. The report will also be of interest to design engineers concerned with the design of roadside hardware. The report will also help policy makers evaluate future programs for assessing the performance of common roadside hardware during vehicle collisions.




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<b>16. Abstract</b> Current Federal Highway Administration (FHWA) models were reviewed and the key mathematical formulations important to roadside hardware were defined. The review included identification of the important handling models as well as finite element based formulations. An outline for a single common user interface that organizes and automates data communications between and among the modeling capabilities was prepared.  A survey of the vendors of nonlinear finite element analysis (FEA) codes was conducted as well as the collection of data defining computational requirements for the types of problems the FHWA would be considering in the design process. These data formed the basis for a recommended nonlinear FEA code. This study concluded that the public domain version of the DYNA/NIKE suite of codes was preferred.  A prototypical single common user interface was constructed and demonstrated. This demonstration software contained example programs of various kinds to illustrate functionality and key simulation technologies that should be developed in addition to nonlinear FEA. In particular, a prototype interactive vehicle dynamics model (IVM) was demonstrated. The interactive vehicle model demonstration was used to illustrate a "drive-through" capability for evaluating roadway design created on computer aided roadway design systems.			
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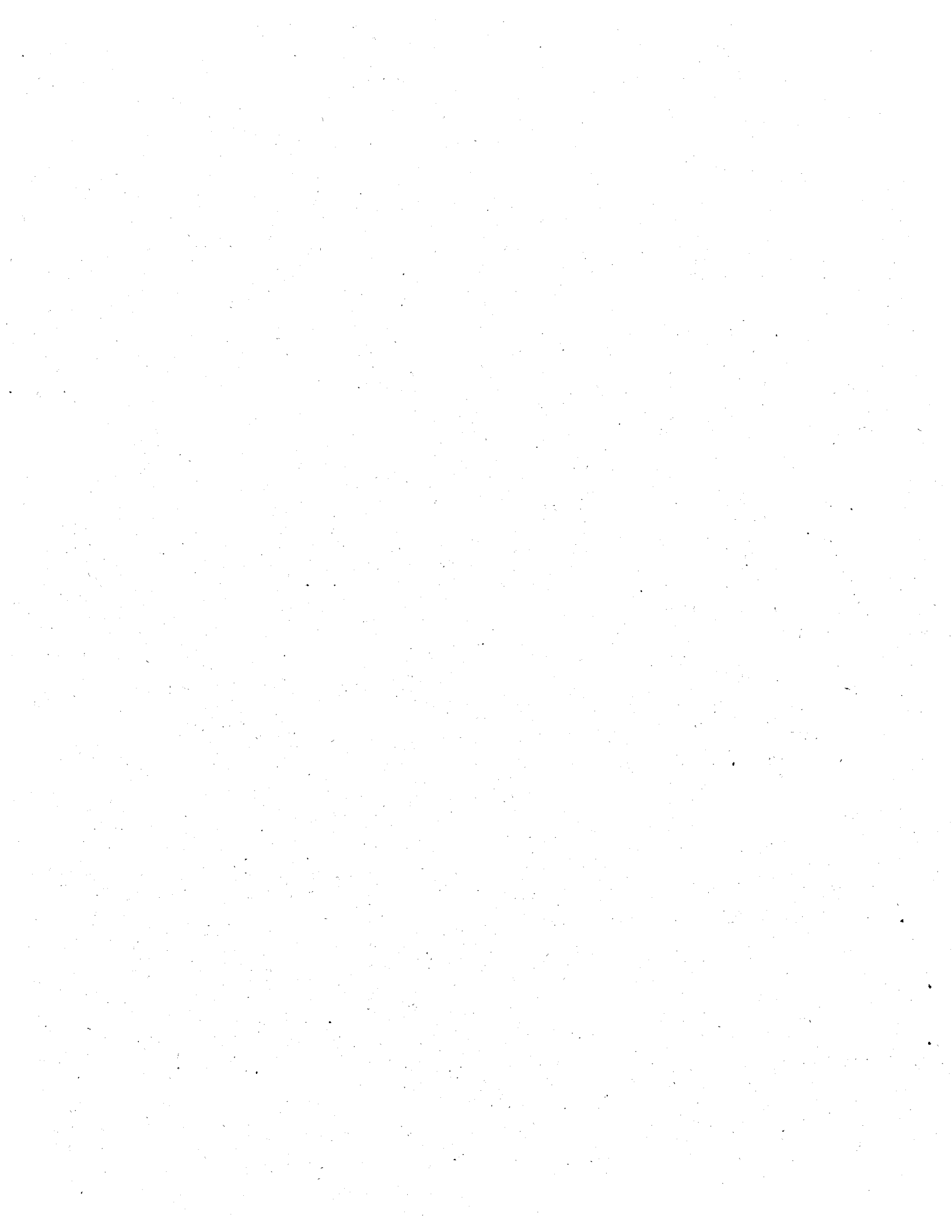
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## 1.0 INTRODUCTION

The Federal Highway Administration (FHWA) has several computer models that have been used to improve accuracy of engineering calculations associated with design of roadside hardware. This report documents the development of a plan to improve the accuracy and efficiency of roadway safety computer modeling capabilities.

Current FHWA models were reviewed, and the key mathematical formulations important to roadside hardware were defined. The review included identification of the important handling models as well as finite element based formulations. An outline for a single common user interface that organizes and automates data communications between and among the modeling capabilities was prepared.

The key finite element formulations formed the basis for requirements to be used in an evaluation of current state-of-the-art nonlinear finite element analysis capabilities. A survey of the vendors of these codes was conducted as well as the collection of data defining computational requirements for the types of problems the FHWA would be considering in the design process. These data formed the basis for a recommended nonlinear FEA code. This study concluded that the public domain version of the DYNA/NIKE suite of codes was preferred.

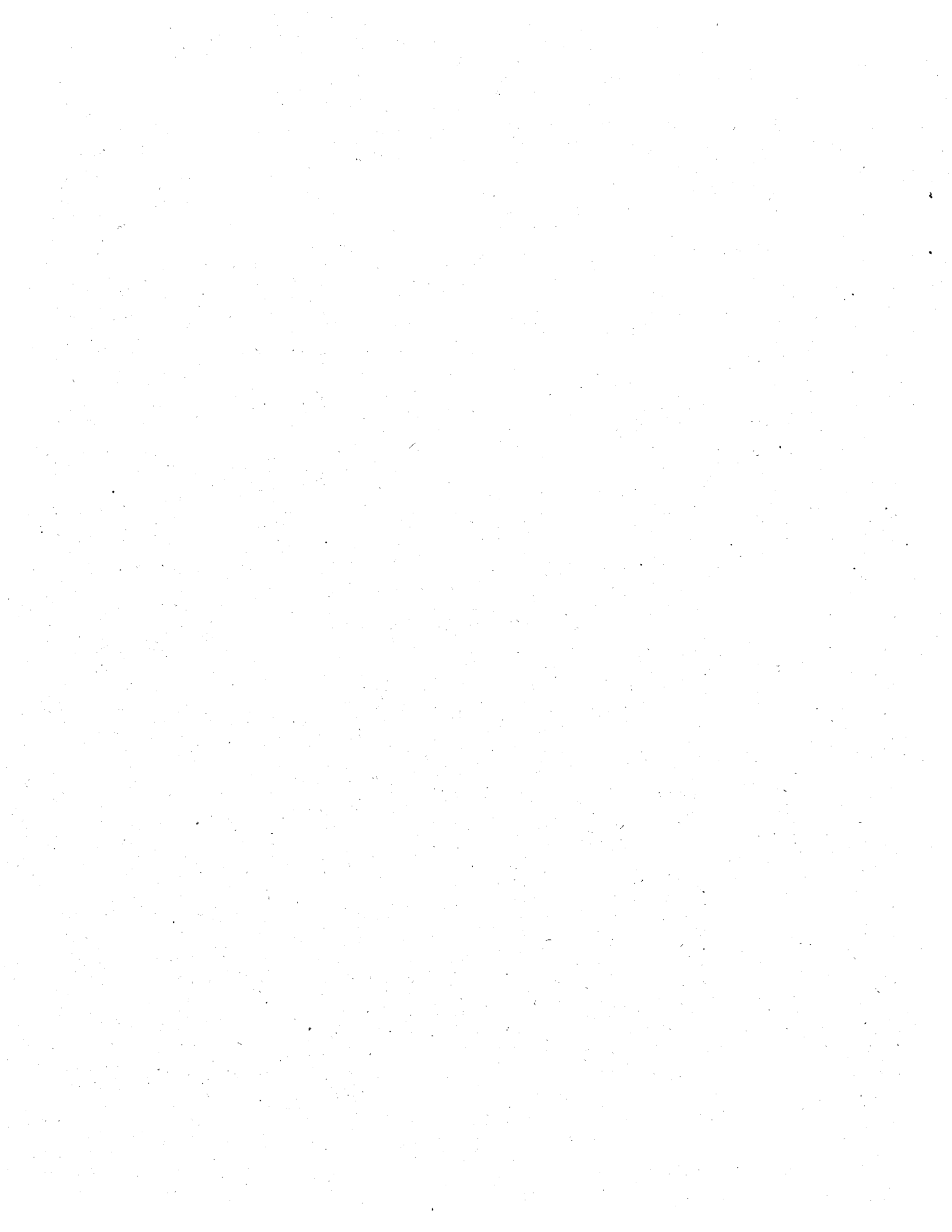
A prototypical single common user interface was constructed and demonstrated on an FHWA workstation. This demonstration software contained example programs of various kinds to illustrate functionality and key simulation technologies that should be developed in addition to nonlinear FEA. In particular, a prototype interactive vehicle model (IVM) was demonstrated.

A comprehensive upgrade plan was prepared that formed a vision for the Roadway Safety Analysis System (RSAS). The fundamental requirements of the system were:

- The RSAS should be *accessible* to Bachelor of Science level transportation engineers.
- The RSAS should be *flexible* to allow for new theoretical developments, improvements, and expansion.
- The RSAS simulation and modeling capabilities should be *validated* for the design of roadside safety structures and the development of Federal standards and regulations governing safety structures and possibly motor vehicles.

The plan also included tasks that recommended leveraging other FHWA developments in the areas of composite materials and driving simulators to enhance the system and its overall value to the FHWA.

A follow-on task to further refine the interactive vehicle model demonstration to illustrate a "drive-through" capability was also carried out on this contract. The drive-through capability will eventually combine vehicle dynamic modeling technology with roadway design and visualization technology to give the designer an interactive tool for assessment of vehicle interaction with computer-generated roadway designs.



## 2.0 REVIEW OF EXISTING MODELS AND THE SINGLE COMMON USER INTERFACE (SCUI) OUTLINE

This review included the impact models <sup>(1,2,3)</sup> and the handling models <sup>(4,5,6)</sup> described in the list of references in appendix A. Impact model descriptions from GUARD, CRUNCH, and WRECKER were reviewed. Handling model descriptions from GUARD, CRUNCH, HVOSM, T3DRS, T3DRS/SLOSH, and reference 7 <sup>(7)</sup> were also reviewed. (Reference 7, "Investigation of Tire-Pavement Interaction During Maneuvering" fits most appropriately within the handling model capability as a preprocessing calculator of tire-pavement handling properties from a finite element model of the tire road interface. This interaction is typically measured empirically on a dynamic tire testing machine. Thus even though the formulations contained within this reference are nonlinear finite element analytical constructs, it is a significantly different capability than the impact formulations in GUARD, CRUNCH, and WRECKER. In conversations with the COTR, it was concluded that reference 7 formulations should not drive the focus of the review away from the capabilities relating most specifically to the modeling of vehicle interaction with roadside hardware.)

The results of this review are summarized in two parts:

- The Key FEA Formulations From Impact Model Reviews.
- The Outline of the Single Common User Interface (SCUI).

The key FEA formulations established the basis for the nonlinear FEA evaluation. The SCUI outline contains requirements which drove the prototype software system described in detail in chapter 3 of this report.

Three assumptions were made during this review: First, the Roadway Safety Analysis System should be accessible to Bachelor of Science level engineers; the FHWA desired a flexible system to allow for new theoretical developments and improvements to specific capabilities; and the overall goal of this effort was to develop a system of validated simulation and modeling capabilities for the design of roadside safety structures.

### 2.1 KEY FEA FORMULATIONS IDENTIFIED

#### Review of Previous FHWA Impact Models

- 3D convected coordinate beams.
- Convected coordinate plate elements.
- Cable element with geometric stiffness.
- Crash cushion elements.
- Soil/Post 3D nonlinear beam elements.
- Collapsing ring element (3D nonlinear spring element).
- Rigid links.

- Compressive axial springs.
- Tire and tire-roadway friction elements.
- Model integration with rigid body models of vehicle dynamics.
- Rigid medians.

**Features Mentioned in FHWA Needs Analysis (Attachment 7 to the Request for Proposal) including:**

- General 3-D contact-impact.
- Frangible slip plane models for luminair pole base supports. Need to account for the substrate compliance in modeling the relative bending versus shear stiffnesses and strengths.
- Geometrical stiffening of guardrail sections due to fixity conditions at posts. (Open web cross sections where warping constraints increase stiffness.)

**Features Mentioned in Verbal Conversations with the COTR**

- Composite materials.
- Macro elements.

Each of these formulations and their application to roadside safety design will be explained in chapter 2.

## **2.2 THE OUTLINE OF THE SINGLE COMMON USER INTERFACE (SCUI)**

### **Preliminary Functional Specification**

**High Level Graphic Programming Language Based on Graphic User Interface Standards, X-windows and MOTIF.** The SCUI should allow interactive construction of executable networks (runstreams) among the available applications programs. Some representative runstreams are:

- **Coupled Rigid Body Dynamics (RBD) and FEA**—simultaneous integration of RBD equations of motion with structural equations for the deforming regions of the domain.
- **Uncoupled RBD and FEA.**
  - FEA is used to get response of structural elements condensed to a minimal set of degrees of freedom (DOF) and this is ported to a RBD simulation where iterative design studies are performed that do not require detailed knowledge of the structural response.
  - RBD simulations are used to define the initial conditions for impact scenarios, or load cases for detailed design of particular components.
- **Interactive RBD.** A real-time or near real-time simulation of a vehicle is controlled by interactive user inputs that control the vehicle speed and trajectory on-line. If the interactive input device is an imitation of a steering wheel and dashboard with gas and brake pedal as well, the workstation becomes a general purpose emulator.

**Pre- and Post-processors.** For many commercial applications these already exist. The goal of the SCUI will be to improve their functionality without requiring significant modification to the package itself.

**Auxiliary Processing.** A mathematical analysis capability that augments the capability of the pre- and post-processors. Also if validation is included in the system requirements, a test data analysis package will be needed that can capture data from videos and perform various test data analysis calculations (auto and cross spectrums, coherence, percent error and statistical analyses).

**Data Bases and Data Structures.** The I/O requirements below show some of the requirements of the existing programs. Generally the requirements will be the same for any capability that contains the same essential mathematical model types (RBD and FEA). The data base, along with NFS and NCS, should automatically handle the major data transactions required by the executable networks (runstreams) identified above. The data base should be hierarchical and cross referenced according to its historical origin, functional class, and any other significant associativity rule. The data base should be used to catalog test data and historical analysis results.

**Communications.** This includes networking and external communications. Since the networking capabilities for workstations and personal computers (PC's) differ greatly, this will depend on the hardware system. Workstations can be linked via the network file system (NFS) and the network computing system (NCS) to give a network of workstations the appearance and power such that the whole is at least equal to the sum of its parts (i.e., sharing disk and central processing unit [CPU] power seamlessly). Analogous systems for heterogeneous and PC environments do not exist.

External communications to other networks or computers will be required. The quality of this communications link depends on the kind of remote computing to be done. For example, larger problems may be required that do not fit on a workstation. With some training, the analyst can learn to use supercomputing more cost effectively than the workstation for some problems. If large data files are to be transferred, a high-speed dedicated telecommunications link will be required.

**User Friendliness.** This will consist of a Users Manual as well as an online helps system for complex analytical runstreams. Also covered under this item is the possibility of including closed form solutions to design problems where appropriate. For example, the simplified models of truck braking and handling available through the University of Michigan Transportation Research Institute could be integrated into the system.<sup>(3)</sup> Another example of this would be a material properties data base.

### **Program Structure**

The SCUI will take advantage of the X-windows and MOTIF standards for graphical

user interface programming and some type of high level graphic programming language (HLGPL). Interfaces or 'filters' to the HLGPL from the various applications will permit access to the user. A data base management system will manage the major scratch file handling that usually accompanies major applications codes such as FEA and visualization. NFS and NCS will permit "seamless" integration of the network so that runstreams involving executables and files on several different workstations are possible. The graphic user interface "look and feel" should be significantly independent of hardware, firmware, and operating system. See figure 2.2.1.

### **Preliminary I/O Requirements**

#### **Existing Model Classes of Data: Input**

- Vehicle Mass and Inertial Properties.
- Suspension data.
- Tire-pavement interaction.
- Trajectory and trajectory control.
- Roadside structural hardware data.
  - locations.
  - geometry.
  - structural response and material data.
- Impact interaction model data.
  - crush properties.
  - panel geometric definition.
  - algorithmic controls.

#### **Existing System Classes of Data: Output**

- Vehicle system motion.
- Interaction forces.
- Steer and brake trajectory control inputs.

### **Hardware, Software and Firmware Recommendations**

- **Graphic user interface toolkit**—X- windows, MOTIF, and perhaps some high level graphic programming language.
- **Nonlinear FEA**—see Task B.
- **Hardware**—Workstations are preferred, PC's can be integrated but will be less capable and will require more ad hoc tailoring.
- **Software**—Validation and test data analysis, geometry generation and animation (MOVIE.BYU), NFS, NCS, CROSSTALK, a general rigid body dynamic capability with exact formulations for kinematics of suspension and trailer linkages.

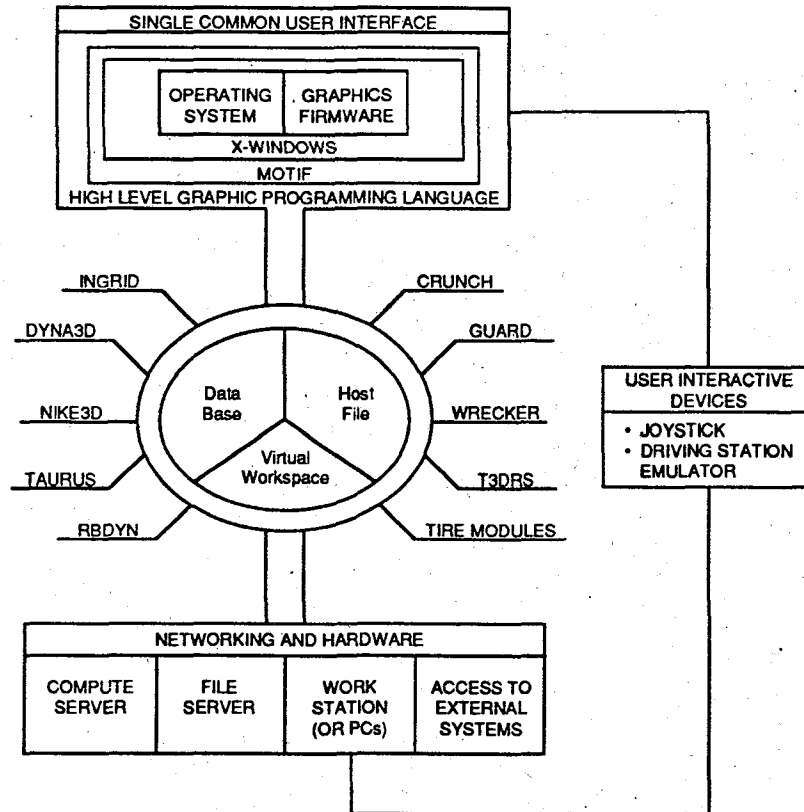
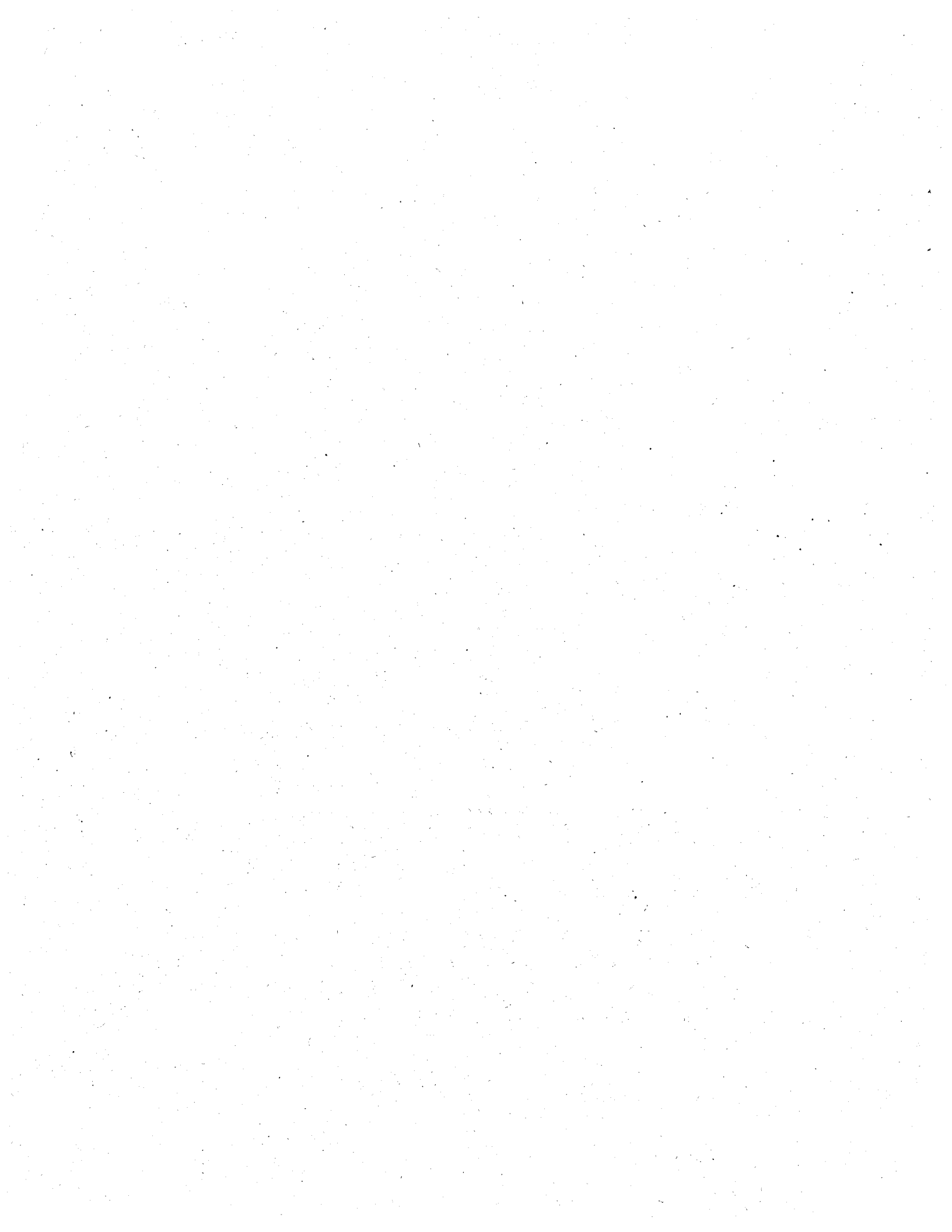


Figure 2.2.1 Conceptual structure of the single common user interface.

- **Firmware**—modem and graphics cards for PC's, high-speed graphics engines with workstations, communications ports to support interactive devices.
- **Distribution of software to the appropriate hardware**—All handling models should be able to run on a PC. Nonlinear FEA will require a workstation. This workstation will function as the main compute server with some applications having the compute load distributed across the network to two or more machines as well via remote procedure calls made possible through NCS. Multiple hard disk units associated with the workstations can function as the file server using NFS.



### 3.0 NONLINEAR FEA CODE EVALUATION AND RECOMMENDATION

This chapter summarizes the results of the task B effort to evaluate available general purpose nonlinear finite element codes with respect to their ability to meet FHWA requirements. This task consisted of a requirements analysis, a survey of selected nonlinear FEA codes, and an Inventory Exercise to identify the issues confronting new users of nonlinear FEA codes. Also included in this assessment is a table comparing the computational power required to run representative nonlinear FEA problems. The requirements used in this evaluation were derived from four sources:

- The review of impact models.
- Attachment 7 to the request for proposal (RFP).
- Conversations with the COTR.
- Opinions of experts in the field of nonlinear FEA.

#### 3.1 NONLINEAR FEA REQUIREMENTS ANALYSIS

This document defines the FHWA nonlinear FEA requirements as identified in 1) the task A impact model review, 2) the summary of current model capability limitations (Attachment 7 to the RFP), and 3) subsequent conversations with the COTR concerning: a) FHWA computer hardware availability, b) design objectives, c) projected uses of the nonlinear FEA capability, and d) target users. Associated with each of the requirements are notes of explanation and a summary of the survey results.

**General 3-D Contact.** The current contact elements are vertical planes or panels on the vehicle whose intersection with element contact lines are monitored and computed. Interaction forces are applied based on the crushing characteristics of the vehicle panel. This procedure implicitly assumes that the macroscopic stiffness of the vehicle structure is significantly less than that of the barrier. In many cases this is a good assumption. With cables and some guardrails it may not be valid.

To date, commercial FEA codes have developed two basic kinds of contact algorithms: gap elements and slide lines. There are many variations on these two general categories that depend on element type and relative stiffness of the impacting bodies. This is a very active area of current research and all of the vendors are protective of their latest developments and plans in this regard. To take advantage of these capabilities with any code, the FHWA would need to increase its computer capacity to at least include a high performance super-workstation (e.g., 40 Mips, 256 Mbytes of RAM and 8 Gbytes of disk) Many of the code developers consider solution of realistic problems involving 3-D contact to be strictly a supercomputer problem, with workstations for visualization and model debug. This feature, plus the use of explicit time integration algorithms, are the principal applications which are driving the development of structural codes suitable for massively parallel supercomputers. The one new contact algorithm actually announced by the vendors was the Belytschko "pinball algorithm" which is most specifically applicable to these computer architectures.

The existence of contact algorithms in a model creates nonlinearities that are not very compatible with implicit dynamical equation solvers. Thus many experts believe that explicit code formulations are the only way to solve large-scale contact-impact and sliding interface problems.

Recent development of element-by-element iterative solution techniques for matrices has some developers optimistic that there is still hope for implicit time integration algorithms (ADINA and NIKE).

**Corotational Element Formulations.** This capability is also referred to as "convected" coordinates in the CRUNCH and WRECKER theoretical manuals. Many of the commercial nonlinear FEA codes have the same fundamental assumptions which allow for large rigid body displacements of elements. It is also sometimes referred to as an "updated Lagrangian formulation." It appears to be a standard for nonlinear FEA codes and leads many of them to claim to be able to handle general rigid body motion. While this is true in the FEA sense, the ability to construct rigid body system dynamic models for vehicle handling simulations is not the forte of these codes or their integration algorithms.

**3-D Nonlinear Macro Elements.** This refers to the capability to compute a local model 3-D nonlinear coupled response and abstract it to a minimal degree-of-freedom element that can be replicated several times in a model. Computationally efficient post-soil interaction, circular collapsible ring elements and guardrail sections are drivers for this requirement. The derivation of coupled nonlinear 6 DOF elements requires some care. Most of the vendors responding assumed no coupling between the DOF. ANSYS allows a general 6X6 linear stiffness matrix.

To generate the response curves of a macro element it is convenient to have substructuring available for linear elements and nonlinear static analysis capability for the others. DYNA is only a transient dynamic code and therefore must rely on NIKE, its implicit formulation counterpart, to perform these analyses most efficiently. Lawrence Livermore National Laboratories (LLNL) has recently created the capability to port static solutions from a NIKE analysis to DYNA as initial conditions for dynamic simulation. This precludes the waste of compute cycles to obtain static equilibrium in DYNA. Thus, having both implicit solution capabilities for static analysis, and explicit for dynamics is desirable.

ABAQUS and MARC also offer both implicit and explicit solvers. MARC apparently uses the same element formulations for both cases. Similar to the DYNA/NIKE philosophy, HKS is writing a completely separate code, ABAQUS/Explicit, for explicit dynamic analysis. But, the use interface is designed to be almost identical to the original implicit ABAQUS code.

**General Elastic-Plastic Beams With Warping.** The beam element technology must be general enough to handle open sections and the effects of warping, as well as the development of plastic hinges. This is not a difficult feature to add to a code but the different ways in which the codes approach it demonstrates their user friendliness philosophy. For example, DYNA assumes the user will be able to define his own cross section integration rule. The ABAQUS approach takes the user input as a general section and computes the appropriate equivalent beam section properties from the defined geometry.

**Post/Soil Modeling.** Detailed modeling of post/soil interactions is required in order to generate the nonlinear coupled 6 DOF response of a macro element that can be used to speed up crash simulations without sacrificing accuracy of the post/soil response. These models can also be used to optimize post/soil designs. Soil modeling under differing conditions of saturation and soil type are required from the FEA code.

While most of the codes have basic soil models including the effect of pore pressure (hydrostatic load stiffening), DYNA in particular has the widest variety of material behavior models.

**Interface to Rigid Body Vehicle Dynamic Simulations.** The CRUNCH program switches control of the simulation from the vehicle handling program for the pre-contact phase, to the interaction module which drives the barrier module. The barrier module is the nonlinear finite element analysis portion of the simulation. For the post-contact phase, the vehicle handling program resumes control.

If a commercial nonlinear FEA code were used, the data interfaces to rigid body dynamic simulations would be required. Accomplishing this interface between the vehicle handling portion of the simulation and the impact portion can be accomplished a number of ways. Some FEA codes have built the vehicle handling simulation into the FEA code by modifying the source code significantly. On the other hand, the transfer of initial conditions for incipient impact from a rigid body dynamic simulation to a FEA simulation is not a complex task either. PAM-CRASH has been integrated with rigid body codes for simulation of rollover events. DYNA has been integrated with MADYMO, an anthropomorphic dummy model that uses discrete rigid body elements. This integration is one driving requirement in the SCUI.

**Crash Cushions.** The current code uses plane triangle elements to model the space occupied by a number of discrete crash cushions as a continuum with gross crushing and energy absorbing properties. Nonlinear FEA codes that allow user supplied material yield criteria and hardening laws can be used to construct equivalent models. This is not seen to be a difficult problem for any code using the current formulation, but a formulation based on first principles might be a much more significant problem. See requirement on buckling and wrinkling below.

**Rigid Medians.** Rigid surfaces are a standard feature of most nonlinear FEA codes. Their interaction with deformable surfaces are important parts of almost all of the sliding interface capabilities surveyed.

**Cable Elements.** Geometric stiffening is the significant phenomenon required in these elements. The use of a corotational element formulation will automatically model the geometric stiffening effect. Rayleigh damping or nodal damping can be used to damp out spurious oscillations.

**Cables Slipping Out of Hook-eyes.** Conditional fixity conditions on standard cable elements are the most obvious solution to this. Most codes contain elements for unidirectional response, however the precise logic to be implemented would probably require user supplied coding in order to model the fact that the cables will slip out only if load is applied in a particular radial direction and, once it has slipped out, it is completely free.

**Frangible Slip Planes.** Models of the details of luminaire supports will be necessary to support the design of these devices and the simulation of their behavior during vehicle impact. In particular, the models must include the relative stiffnesses of the support in bending versus shear and the effect of the mounting foundation mass and substrate compliance on the results. This might be another candidate for macro-element generation.

Detailed modeling of this application will require the use of releasing or eroding elements or some similar construct that accurately models the bolt failure in combined bending, shear, and axial load that dynamically establishes the new free surfaces where failure occurred. This is a modeling issue that will probably require some user code for most codes with the possible exception of LS-DYNA.

Less detailed models of this device can be done in almost any of the codes using 6 DOF nonlinear releasing spring elements. However this would require either test data or response data generated from a series of quasi-static runs using a detailed model.

**Buckling and Wrinkling.** Use of nonlinear FEA to predict end-on impacts of guardrails is required. Linear buckling analysis is available in many of the more commercially oriented codes. However, for FHWA purposes, nonlinear buckling and post buckling simulation is required.

This behavior naturally evolves from the system dynamics in an explicitly formulated code, but the asymmetry that governs the direction and location of hinge points and localized behavior must be introduced by the analyst. Thus all of the explicit codes will, by default, contain this capability if shell element models of the guardrails are used. If beam element models of guardrails are used, wrinkling and localized behavior of the cross section will not be captured.

**Eroding Mass Crash Cushion.** This is a very special need that none of the nonlinear FEA codes could be expected to have. Sand in plastic barrels has little structural strength beyond that created by the barrel and the confining pressure on the sand. This situation could likely be modeled by some macroscopic model that accounts for individual barrels, their interactions, rupture, and the transfer of momentum, but does not attempt to model the sand as an eroding continuum.

However, should it be of interest, macroscopic models could be used to define the realistic boundary conditions and initial conditions for doing detailed analyses of barrel design that do include the eroding continuum. DYNA would probably be the most qualified code for this application as it does have some erosion capability.

**Effect of Slotted Holes in Guardrails.** The use of nonlinear springs on the beam element interfaces with their post supports could be constructed with standard elements in most of the nonlinear FEA codes.

**Virtual Domains.** This refers to the ability to define domains of elements whose inclusion in the analysis is conditional. Thus the total computational requirements are minimized as elements are added and deleted based on their proximity to the impact point. From a code formulation point of view this capability is very similar to the rigid body simulation integration and the erosion code capability in which automatic restart and reformulation of elements and their domains, boundary conditions, and initial conditions occurs based on the occurrence of particular events.

**Composite Material Modeling Capability.** The FHWA may be required to assess barrier and roadside hardware made of composite materials.

**User-Friendliness and Support.** The use of artificial intelligence, or an expert system rule base that circumvents the need for the analyst to be familiar with the details of element formulations and clever "tricks-of-the-trade" would be very helpful in a nonlinear FEA code. Nonlinear material behavior is complex in its own right and the programming of features that automatically account for known physical constraints and modeling rules would be very helpful.

The commercial codes are already including many of these features such as automatic time step control in explicit codes, restart, rezoning, subcycling (mixed time step integration), and h-adaptivity. The more commercialized codes also offer better pre- and post-processing, documentation, examples manuals (very helpful in many cases), and hotline support.

The less commercialized vendors usually accommodate customers by creating custom versions of public domain or research codes. The upfront code costs are less but the documentation, features, and support are significantly less adequate. Consulting is the main business of these vendors.

Public domain codes and their documentation are typically very terse and inadequate. However access to source code can overcome this problem for the determined and qualified user. The LL-DYNA code is somewhat unusual in that, although the code is public domain, it is still maintained, enhanced, and supported by the government lab where it was developed.

**Cost.** Since FMC is not a purchasing agent of the FHWA, cost data could be obtained on a voluntary basis only. The PC version of DYNA was the only vendor to give this information. However, the LL-DYNA code is in the unusual situation of actually having public support for maintenance and development, and is available at no cost.

**Computer Requirements.** Many of the nonlinear FEA codes are being written to run on only certain classes of machines. The FHWA appears to be limited to the use of a super-workstation, at best, and would like to see much of the Roadway Safety Analysis System running on personal computers. While it is possible to port almost all of the codes to a PC, the computer requirements should really be driven by the types of problems and the level of model resolution required to achieve the accuracy desired. The experience gleaned from the new user task indicates that most significant problems will require memory and disk storage that is beyond the practical limits of personal computers.

### 3.2 SURVEY AND SURVEY RESULTS

Appendix A contains the vendor survey form and the list of vendors to which it was sent. The results of the survey have been summarized in the table 3.2.1. It should be noted that this table represents results from surveys received in October 1991.

### 3.3 NEW USER ISSUES

General 3-D contact between and among deformable bodies is a complex phenomenon and the modeling capabilities to represent them are equally complex. Also, the material behavior is in the large strain, elastic-plastic regime and includes the need for accurate rupture, tearing, and shear failure models. Analysis and design of structures under these loading and failure conditions requires significant expertise in computational mechanics. The FHWA should expect that the development of this capability is not trivial. Therefore, the relationships that the FHWA develops with experts in this field, and in particular, the developers of the specific code chosen, are essential to successful application of this technology.

A new user task (documented in appendix B) was designed to objectively identify the types of issues that would confront the FHWA in developing nonlinear FEA expertise. The results of this exercise can be summarized by the following conclusions:

- The FHWA personnel will need to develop proficiency in nonlinear material behavior modeling.
- Development of a nominal level of proficiency with contact algorithms, their theory and control parameters, and the steps involved in their practical application requires 6 to 12 months of dedicated work and study by an analyst with prior knowledge of linear FEA.

Table 3.2.1. Results of survey of nonlinear FEA codes.

Requirements	Code	ABAQUS	ADINA	ANSYS	LL-DYNA 3D	LS-DYNA
1. 3-D Contact		ABAQUS/Explicit Due out in 1992 gaps, slidelines available in standard code Kinematic approach to contact problem	Gaps, slidelines Implicit, element by element iterative solver	Rev 5.0 due out in January 1992 has element to node contact surfaces gap elements Implicit solver Good Pre-processor	Contains a library of interface elements include several different types of slidelines Explicit solver	Same as LL-DYNA Enhanced contact algorithms Due out in Jan. 1992
2. Corotational Element Formulation		Yes	Yes	Yes	Yes	Yes
3. 3-D Macroelement Capability		Multi-level linear static and dynamic stress recovery, stress stiffening, replication, standard implicit ABAQUS for development of non-linear elements	Linear static and dynamic substructuring stress recovery quasi-static analysis for non-linear element response	Multi-level linear static and dynamic, with stress recovery and replication. Non-linear formulations can be done Linear 6 DOF coupled element	No true substructuring Clever analyst can accomplish w/slide lines. Use NIKE for efficient quasi-static analysis	Same as LL-DYNA
4. Beams		Finite strain torsion and warping functions General section, easy user input	General beam element	General beam element	General beam element allows almost arbitrary cross section Requires user defined integration rules	Same as LL-DYNA
5. Soil-structure Interaction		Yes	Yes	Yes	Transmitting boundaries permits semi-infinite media modeling Wide variety of material models	Same as LL-DYNA
6. Rigid Body Simulation interface		Untested, possible	Untested, possible	Untested, possible	Rudimentary, embedded capability	Interface under development for MVMA
7. Crash Cushions (as formulated in CRUNCH)		Yes User-supplied Material model	Yes User-supplied Material model	Yes User-supplied Material model	Yes User-supplied Material model	Yes User-supplied Material model
8. Rigid Medians		Yes	Yes	Yes	Yes	Yes
9. Cable Elements		Yes	Yes	Yes	Yes	Yes
10. Cable hook eyes		User coded	User coded	User coded	User coded	User coded
11. Frangible slip planes		User coded	User coded	User coded	User coded	Possible with latest version
12. Buckling and Wrinkling		Buckling — yes Post buckling — Riks analysis Wrinkling — yes	Buckling — yes Post buckling — Riks analysis Wrinkling — yes	Linear buckling Implicit solution for quasi-static simulation of post-buckling Wrinkling — yes	Naturally evolve from highly discretized first principles analysis No classical solutions are available	Same as LL-DYNA
13. Eroding mass crash cushion		Probably significant user code	Probably significant user code	Probably significant user code	Probably significant user code	Probably significant user code
14. Slotted holes in guardrails		Yes	Yes	Yes	Yes	Yes
15. Virtual domains		No	No	No	No	No
16. Composite material modeling		Yes	Yes	Yes	Yes	Yes
17. User orientation		Excellent restart, rezone Automatic time and load step controls Graphics pre- and post-user code available elements mat'l, loads and constraint equas.	Restart, rezone Auto time stepping Graphics pre and post user code available for elements, mat'l models and loads	Excellent restart, rezone, auto mesh, auto time step control Graphics pre- and post-user code available elements material laws, constraint equas.	Restart, no rezone Auto time step Graphics pre and post (window based workstation is very helpful) lots of mat'l models source code available	Same as LL-DYNA Except: 1992 addition subcycling, interactive graphics; mat'l models user contact & mat'l models; other visualization interfaces
18. Cost		Proprietary Commercial code not in public domain	Proprietary Commercial code not in public domain	Proprietary Commercial code not in public domain	Public domain Distributed and supported by Lawrence Livermore Labs	Proprietary commercial code
19. Target class of computers		Workstations and supercomputers	PC's, Workstations & supercomputers	PC's, Workstations & supercomputers	Workstations and supercomputers	Workstations and supercomputers (PC insufficient)

Table 3.2.1. Results of survey of nonlinear FEA codes (continued).

Requirements	Code	MARC	PAM-CRASH	PC-DYNA	SPECTRUM 331	SUPERWHAMS
1. 3-D Contact		Gaps and sidelines Kinematic constraint approach Explicit integration is available	Same as LL-DYNA except tailored for applications and speed; arbitrary self contact; air bag folding and unfolding	Same as LL-DYNA	2-D sidelines (a unique formulation from the HONDO code by D. Sam Key at Sandra Labs)	Pinball algorithm Highly efficient for vectorizing code
2. Corotational Element Formulation		Yes	Yes	Yes	NO, but easy to modify	Yes
3. 3-D Macroelement Capability		Multi-level quasi-static; stress recovery; replication; implicit solution for quasi-static response	Same as LL-DYNA Example at 6 DOF nonlinear element Neck response in humanoid models	Same as LL-DYNA	None	Substructuring Probably the same as DYNA
4. Beams		General library includes open sections	Same as LL-DYNA	Same as LL-DYNA	Not known	Euler Bernoulli; no warping in current version
5. Soil-structure Interaction		Yes	Same as LL-DYNA	Same as LL-DYNA	No	Marginal
6. Rigid Body Simulation interface		Untested, possible	MADYMO and others have been demonstrated Roll-over capability embedded (SAE test)	Same as LL-DYNA	Untested	RB motion is standard feature Ease of use compared to rigid body dynamic system codes is untested
7. Crash Cushions (as formulated in CRUNCH)		Yes User-supplied Material model	Yes User-supplied Material model	Yes User-supplied Material model	Yes User-supplied Material model	Yes User-supplied Material model
8. Rigid Medians		Yes	Yes	Yes	Yes	Yes
9. Cable Elements		Yes	Yes	Yes	Yes	Yes
10. Cable hook eyes		User coded	User coded	User coded	User coded	User coded
11. Frangible slip planes		User coded	User coded	User coded	User coded	User coded
12. Buckling and Wrinkling		Buckling — yes Wrinkling — yes Post buckling — yes	Same as LL-DYNA	Same as LL-DYNA	Similar to LL-DYNA	Similar to LL-DYNA
13. Eroding mass crash cushion		Probably significant user code	Probably significant user code	Probably significant user code	Probably significant user code	Probably significant user code
14. Slotted holes in guardrails		Yes	Yes	Yes	Yes	Yes
15. Virtual domains		No	No	No	No	No
16. Composite material modeling		Yes	Yes	Yes	Yes	Yes
17. User orientation		Excellent restart, rezone, and auto mesh Graphic pre and post auto time and load stepping 70 user subroutines	PATRAN IDEAS Preprocessing proprietary post processor Restart, adaptive meshing is planned but not released User routines planned but not currently available	Same as LL-DYNA	Not well developed Source code available	Pre and post processing not available Restart available h-adaptivity is a unique feature Mat1 & element modification gateways No source code
18. Cost		Proprietary commercial code	Proprietary commercial code	Proprietary commercial code price: approx. \$5000	Not explicitly in the software business	Proprietary commercial code
19. Target class of computers		Workstations and supercomputers	Workstations and supercomputers	Personal computers	Workstations, PC's and supercomputers	Supercomputers and massively parallel architectures

- Every new problem is a multi-step, iterative discovery process in which failed simulation results often demonstrate need for innovative modeling methods or new element or capability derivations. Therefore forecasting labor and computer costs associated with the any simulation should be conservative.

### 3.4 NONLINEAR FEA CODE RECOMMENDATION

The most significant discriminators in this evaluation were the following:

- 3D Contact Modeling.
- Rigid Body Simulation Interface.
- User Orientation.
- Cost.

Several of the best codes have state-of-the-art 3D contact modeling. None of the codes contained general rigid body system interfaces with vehicle handling models. User-friendliness is extremely difficult to quantify, and as the new user task illustrated, any use of nonlinear FEA requires a significant level of experience and familiarity with numerical solutions to nonlinear dynamics problems. In general, it was impossible to distinguish among the commercial codes with respect to cost. However, because one option, the Lawrence Livermore version of the DYNA/NIKE codes, is public domain, this became a significant discriminator. Furthermore, because there were no other significant discriminators, cost becomes the most significant factor. Additionally, the availability of a PC-DYNA code at a nominal cost permits the same code to be used on all computer platforms.

It should be noted that computer capacity requirements for DYNA are dynamic—that is, they are problem dependent. The ability to get the program to run simple problems on a particular computer does not guarantee that the user will be able to solve a significant problem. Furthermore, since the validation of the simulation and modeling capability in the Roadway Safety Analysis System is important, a study of the problem size versus accuracy achieved is required in order to truly understand the computer random access memory (RAM) and disk storage requirements. Table 3.4.1 partially addresses this issue with some small examples and the qualitative experience of several experts in nonlinear FEA. However, every problem class tends to have its own unique requirements.

Enhancements to algorithms and user interfaces is an ongoing and very competitive enterprise among the experts in this field. Therefore it is recommended that, as the development of the Lawrence Livermore codes are pursued, the progress and developments of the following codes and/or vendors also be monitored:

- ABAQUS.
- ANSYS.
- CENTRIC Engineering.
- LS-DYNA.
- MARC.
- MSC-DYNA.
- PAM-CRASH.

All of the organizations developing commercial codes have a strong emphasis on user support and technical achievement that could result in innovations that specifically address the FHWA needs.

**Table 3.4.1. Comparison of computer requirements for representative projected FHWA problems.**

Computer Example Problem	PERSONAL COMPUTER	WORKSTATION	SUPERCOMPUTER
1. Vehicle 3-D Structural Model Impacting Structural Model of Barrier (Over 100,000 elements)	Not possible	Marginally possible	Most appropriate platform
2. Panel contact models and plastic hinge models of vehicle structure and roadside hardware for impact simulation	Possible; memory problems; graphics quality may suffer	Most appropriate platform	Very fast response
3. Detailed model of soil/structure interaction for post/soil 6 DOF nonlinear spring response modeling	Not possible to get accurate results	Marginally possible Requires large memory	Most appropriate platform
4. Collapsing ring 6 DOF Response	Atleast 4 Mb RAM, 100 Mb hard disk, math coprocessor	Accurate model result: CPU time 32 hours Memory at least 45 Mb RAM Underintegrated shell element: 0.08 Mb RAM, 4 CPU hrs	Accurate model result: CPU time 7 hours No memory problems
5. Luminaire support with frangible slip plane	Atleast 4 Mb RAM, 100 Mb hard disk, math coprocessor	CPU time = 6 hours Memory used 1 Mb RAM	CPU time — hours No memory problems



## 4.0 THE ROADWAY SAFETY ANALYSIS SYSTEM DEVELOPMENT PLAN

The foregoing chapters have considered the technical requirements for the Roadway Safety Analysis System (RSAS). This chapter will describe a plan for development of the capability. The nonlinear FEA modeling capability development recommendations were given in the previous chapter and this chapter will focus on the single common user interface, or RSAS, and the plan will assume that the nonlinear FEA capability is also being developed.

The requirements for the RSAS are derived from the original assumptions made during the literature review:

- The RSAS should be *accessible* to Bachelor of Science level transportation engineers.
- The RSAS should be *flexible* to allow for new theoretical developments, improvements, and expansion.
- The RSAS simulation and modeling capabilities should be *validated* for the design of roadside safety structures and the development of Federal standards and regulations governing safety structures and possibly motor vehicles.

Considering these requirements, and the available technology, the following are the recommended features and attributes:

- **X-windows and MOTIF software toolkits** for constructing graphic user interfaces should be used.
- **Tailored graphics programming capabilities** for the automation of complex multi-step analyses should be constructed as the need and opportunity dictate. Capabilities such as the Applications Visualization System (AVS) or EXPLORER, are too general and require too much computational overhead to be currently practical for RSAS.
- **The initial development environment** should be the FHWA's Silicon Graphics workstation running IRIX 4.0.1 operating system. The system should be ported and networked later to other platforms as the user community becomes more clearly defined.
- **The system should be modular** and should support several levels of model resolution. The engineer should be able to get "order of magnitude" answers as well as conducting detailed design studies of localized design features. The integration of special purpose "closed form" design codes (i.e., Roark's Formulas for Stress and Strain) is one example of the low resolution capabilities that could be integrated.
- **A rigid body dynamic modeling capability** should be developed containing a library of modeling elements that allow the user to build models of any highway vehicle with an exact representation of system inertia, suspension kinematics, and any trailer linkage kinematics. This capability should include the ability to run interactively under the control of user inputs through some interactive device. It should also be integrated with the nonlinear FEA capability to allow coupled simulations (i.e., where dynamic exchange of initial conditions and final conditions occurs, contingent on a contact criteria, as discussed in section 3.1, Interface to Rigid Body Dynamic Simulations) as well as the two different types of uncoupled analysis runstreams:

- FEA performs preprocessing calculations for rigid body simulations.
- The rigid body simulation calculates initial conditions for FEA based design studies of roadside hardware designs.

- **Broader goals for the development of validated simulation and modeling capabilities** should be considered in constructing a hardware/software system for the design of roadside safety structures. Therefore it is recommended that the validation and test data analysis requirements also be included in the system requirements. The detailed requirements for a general mathematical analysis capability become more defined in light of this requirement. The specific recommendation for a mathematical applications capability should result from these requirements. Video based measurement of displacement data and the acquisition and processing of this data should also be included.
- **Many utilities** such as text editors and telecommunications are software and firmware options that are “bundled” with workstation hardware. PC’s will require modem cards and file transfer protocols such as CROSSTALK for telecommunications. Text editing is already done on PC’s at the FHWA using WordPerfect Revision 5.1. The ability to port text files to this standard word processing system should be a requirement.
- **The level of capability required** should be determined as external data communications requirements become more defined. At the least, a nominal small file transfer capability that uses standard telephone lines and a modem can be used. As the quantity of data increases, the FHWA should consider dedicated high-speed data transfer lines.
- **Enhancement of existing FHWA design and simulation codes** should be done to take advantage of the powerful visualization tools resident in the Silicon Graphics workstation.
- **The initial RSAS** should be developed around the LLNL nonlinear FEA codes DYNA and NIKE. A dynamic animation code developed by FMC should be used to enhance the post-processing capabilities of these codes.

#### 4.1 RSAS DEVELOPMENT PLAN

FMC's approach to the implementation of this plan is incremental. It will be a requirements-driven design with significant focus on the needs of the end users. Each increment will be valuable as a stand-alone capability but also developed in the context of the long range goals listed above. The initial effort will focus on the integration of the LLNL codes and existing FHWA design codes under a single common user interface. Next, specific capabilities required to simulate, test, and validate will be developed. A comprehensive validation effort will end the development phase of the RSAS models.

In addition to consideration of the specific RSAS requirements, the plan also proposes to begin utilizing modeling and simulation capabilities in two key areas that will leverage the basic technologies being developed and be integrated under the RSAS plan:

- **Development and Validation of Composite Materials For Roadside Safety Structures.**
- **Motion Base Simulation.**

A schematic of the Plan is given in figure 4.1.1. Each of the blocks in this figure are further defined below:

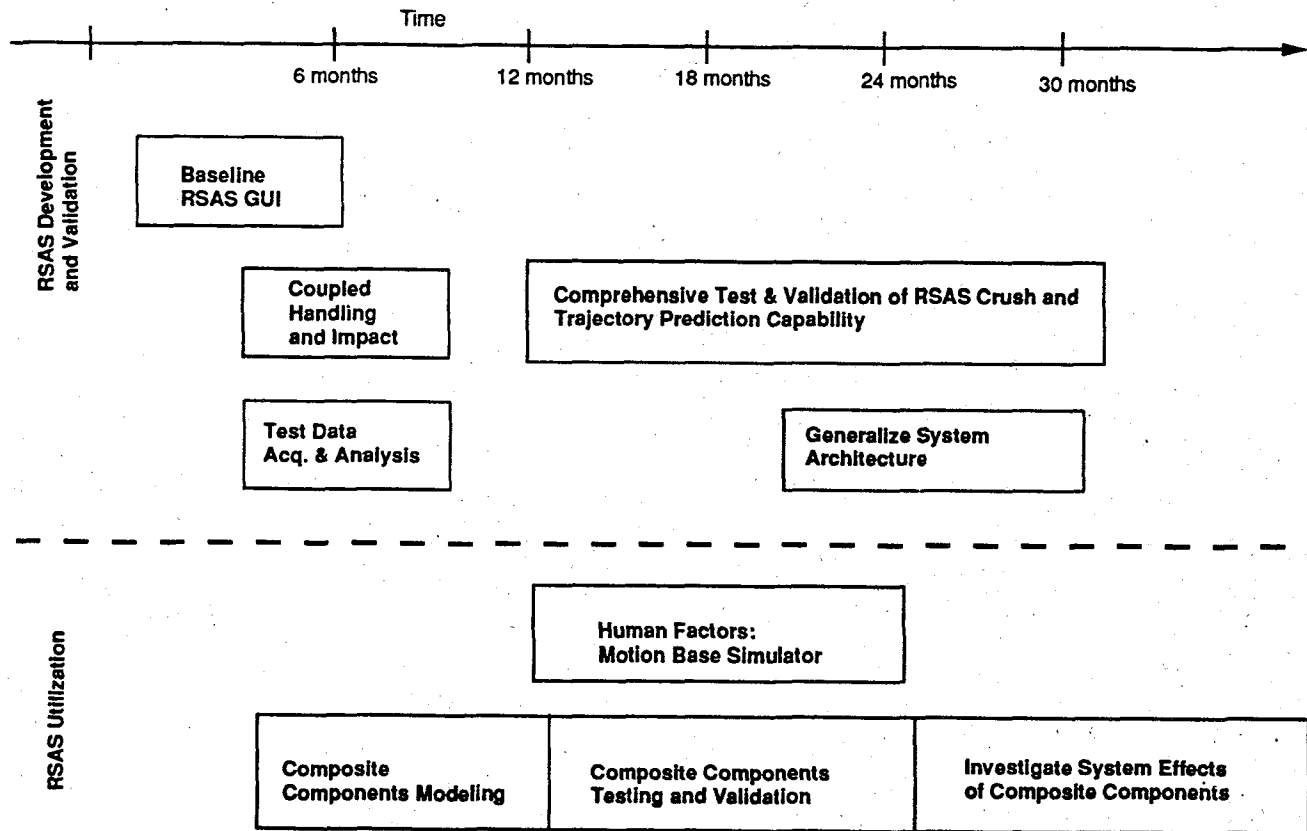


Figure 4.1.1 Upgrade plan for the roadway safety simulation models.

### TASK 1: DEVELOP THE BASELINE ROADWAY SAFETY ANALYSIS SYSTEM

**SCOPE:** A single common user interface will be constructed using the X-Windows and MOTIF software toolkits. This graphic user interface (GUI) will use pull down menus and point and click features to integrate a number of disparate programs including the LLNL FEA codes and their pre-and post-processors and other lower resolution modeling programs requested by the FHWA. Data exchange filters, tailored graphics for existing programs, automated interfaces to word processing capabilities on departmental personal computers and interfaces to other utilities requested by the FHWA will be developed. A preliminary structure of this system is shown in the demonstration single common user interface program structure schematic (figure 2.2.1). A low resolution real-time interactive vehicle simulation of a four wheeled vehicle traveling on a two lane highway with guardrails will be constructed. An animation program for dynamic visualization of nonlinear FEA results from DYNA and NIKE will be developed. This will require some collaboration with LLNL.

### TASK 2: REAL-TIME SIMULATION, OPTIMIZATION, AND RIGID BODY DYNAMIC ANALYSIS DEVELOPMENT

**SCOPE:** Develop the capability of symbolically generating a range of rigid body dynamic analysis modeling elements that can be ported to either a real-time interactive simulation, or a coupled FEA simulation. In both cases the fundamental equations (and computer code) are

exactly the same and originate from the same source. Optimization codes will be developed that will allow the use of performance functionals based on system dynamics (integrals of the equations of motion). FMC's proprietary dynamic analysis capability will provide the basis for this development. Integration algorithms developed at the University of Iowa and FMC will also be leveraged to create a system that constructs a portable rigid body dynamic simulation that is kinematically exact as well as efficient enough to allow it to be embedded in optimization codes and used to drive motion base simulators. Close collaboration with LLNL will be required to correctly integrate the equations of motion into DYNA and NIKE. The concept of virtual domains will be investigated and automated methods for defining standard roadside hardware modeling elements will be developed.

### **TASK 3: DEVELOP TEST DATA ACQUISITION, ANALYSIS, AND CORRELATION CAPABILITY**

**SCOPE:** Develop a system for automated capture and analysis of film and videotape based crash data. This includes old films for which explicit high contrast targets are missing. Develop automated procedures and metrics for reduction and comparison based on FMC proprietary data comparison software. Develop graphical animation and graphic programming techniques that assist the engineer in understanding and recording the data processing schemes as well as visualizing the comparison results. For example, side by side animation of test data with analysis data can often be more valuable than mathematical metrics of comparison during model development. Perform a preliminary validation study by attempting to validate the rigid body motion and deflections resulting from a side impact event.

### **TASK 4: EXPAND RSAS PORTABILITY AND USER COMMUNITY**

**SCOPE:** Develop interfaces to computer-aided design (CAD) systems or other geometric standards that may evolve from ongoing Advanced Research Projects Agency (ARPA) and industry initiatives in Concurrent Engineering. Generalize the RSAS GUI toolkit interface to port to widest range of computer platforms. Define network utilities and interfaces consistent with the evolved suppliers of computing and base of users. Define key interface specifications to allow new FEA codes to interface to RSAS.

### **TASK 5: DEVELOP AND VALIDATE MODELS OF INNOVATIVE ROADSIDE SAFETY STRUCTURES USING COMPOSITE MATERIALS**

**SCOPE:** Leverage proprietary model developments and validation efforts on progressive failure criteria for laminated composite components. These models have been constructed in DYNA-3D. Leverage FMC fiberglass reinforced laminant materials expertise in the design of tracked vehicles to extend their application to highway safety structures. This program would consist of three phases, a model development and material property testing phase, modeling of a composite material component (such as a crash cushion, guardrail end treatment, or luminair support) in the vehicle-structure system, and validation of the predicted effects of introducing the composite component into the system.

### **TASK 6: DEVELOP A MOTION BASE SIMULATOR FOR MEASURING DRIVER RESPONSE DURING VEHICLE-STRUCTURE INTERACTIONS**

**SCOPE:** Use the existing facility at the Turner-Fairbank Highway Research Center to develop a motion base that provides enough motion input to the driver to acquire driver steer and brake responses for various scenarios involving vehicle interaction with safety structures. Alternatively, use an existing facility such as the Iowa Driving Simulator to perform this study.

Determine the minimal motion capability required to obtain the important driver responses that affect roadside safety structure design.

#### **TASK 7: COMPREHENSIVE TEST AND VALIDATION OF RSAS CRUSH AND TRAJECTORY PREDICTION CAPABILITY**

**SCOPE:** Plan and execute a comprehensive program validating the predictive capabilities of the RSAS for the design of roadside hardware and definition of safety standards for its manufacture. The scope of this task will depend significantly on the success of earlier tasks and the identification of the end user and his needs. The task will include specific code developments that are required to validate models of phenomena observed during tests that may not be known at this time. Therefore close cooperation with the DYNA code developers at LLNL is likely to be required.

#### **4.2 DEMONSTRATION SINGLE COMMON USER INTERFACE**

A demonstration single common user interface was constructed to run on the FHWA Silicon Graphics workstation. The demonstration software was constructed consistent with the recommendations listed above. In fact since it was constructed using the X-window protocol, and is modular, it represents a prototype that can be easily upgraded and transitioned into a working Roadway Safety Analysis System.

A structure of the menus available in the demonstration Roadway Safety Analysis System are shown in figure 4.2.1. The highlighted menu items contain actual working copies of software that serve to illustrate key technologies mentioned above. (Note: this menu system has been update to include the capabilities developed under the Phase II work described in chapter 5.

A tutorial for using the demonstrator is given in appendix C.

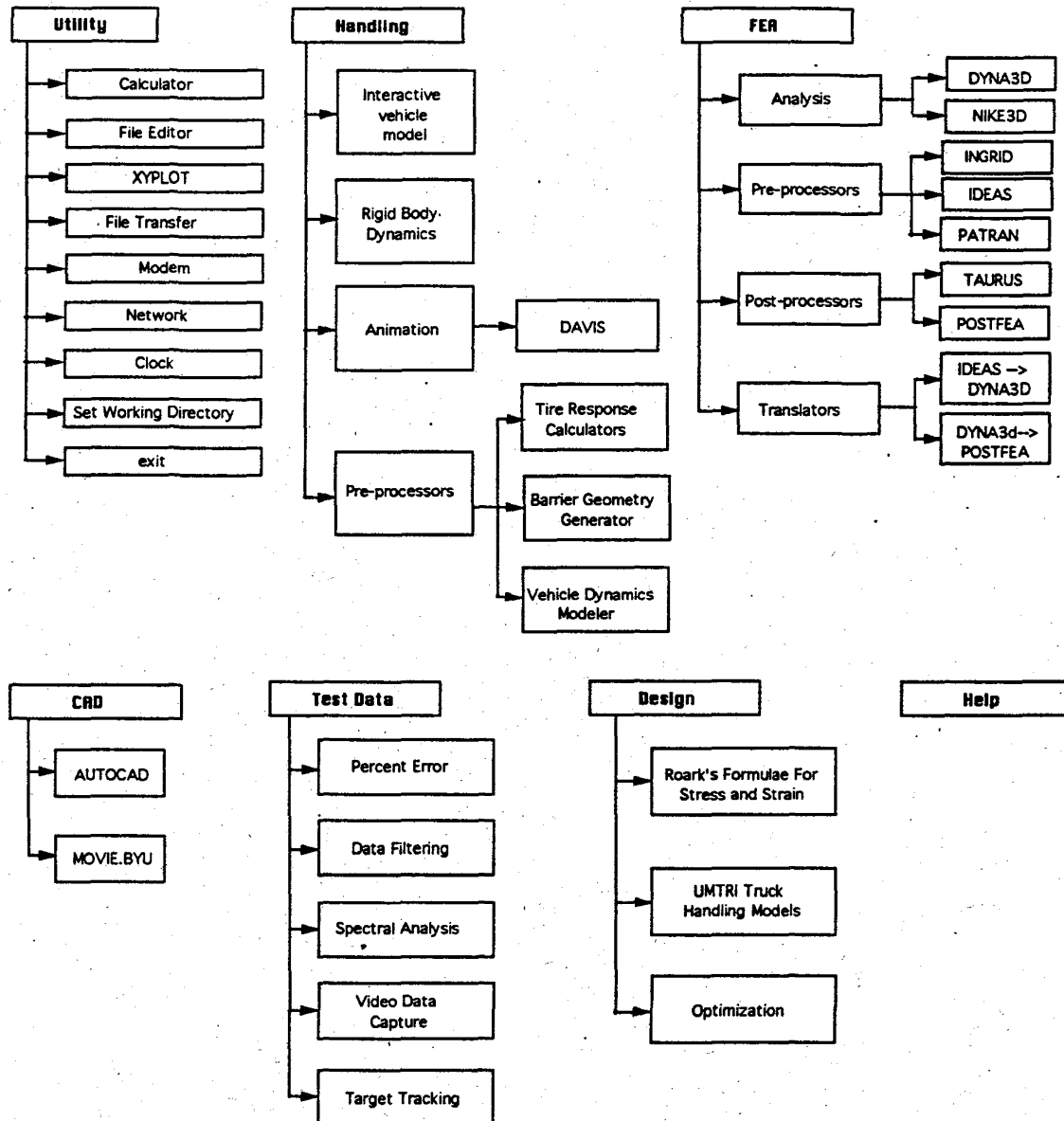


Figure 4.2.1 Menu structure for the Roadway Safety Analysis System (RSAS).

## 5.0 A PROTOTYPE DRIVE-THROUGH CAPABILITY

The original Roadway Safety Analysis System goals stated that it should be accessible to Bachelor's level design engineers. The nonlinear FEA portion of the system clearly requires a higher level of expertise than can be expected of these design engineers. Furthermore, a significant level of CAD capability is already in use by highway designers across the country. However, none of these capabilities allow the designers to test their designs against the performance of actual vehicles while the design is in process.

Consistent with the goals stated in the upgrade plan, an effort to enhance the Roadway Safety Analysis System demonstrator was defined and carried out. Thus, a demonstration "drive-through" capability was developed that would allow a roadway designer to inspect and review a design by driving through it using a computer graphic representation and an interactive vehicle model. This capability attempts to bring two mature technologies together to create a design tool that allows the designer to interact and test a design with a vehicle model. The vehicle model contains the physics of the roadway-vehicle interaction. Through real-time interactive commands, the designer drives the vehicle model down the roadway he has created in a CAD software system.

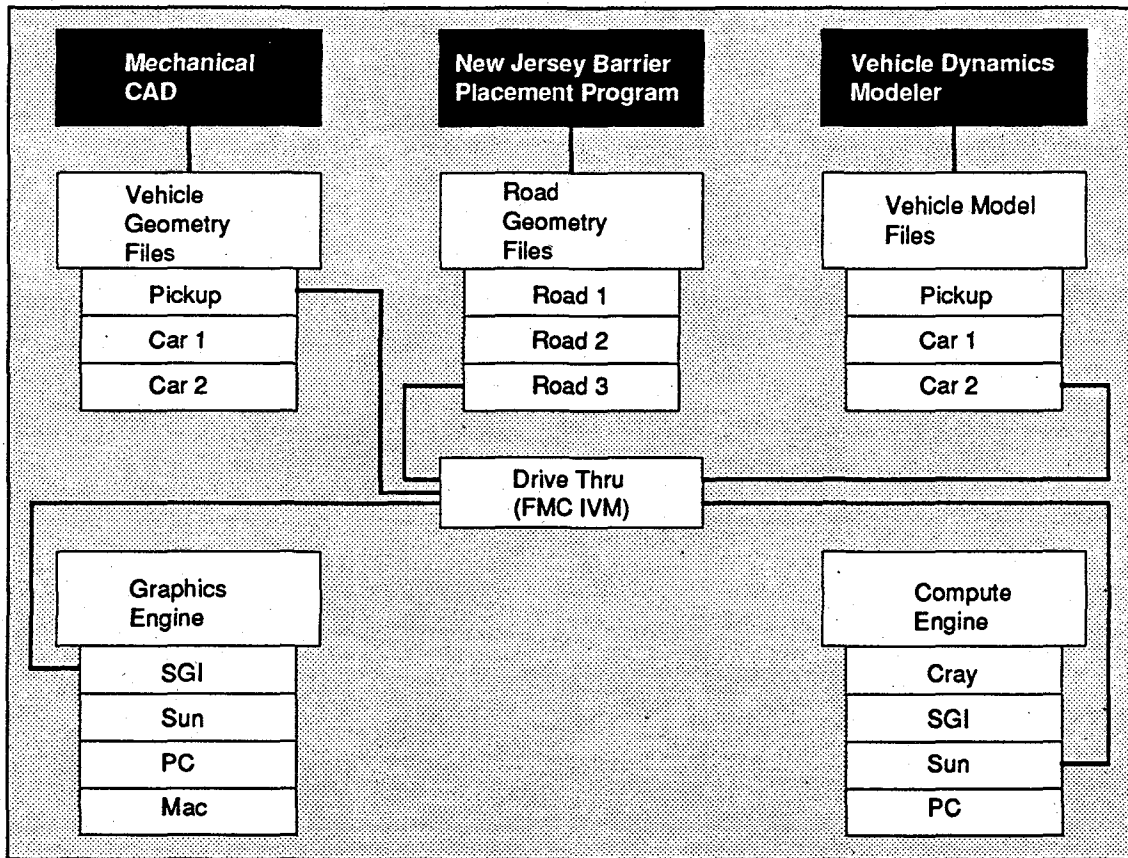
The construction of this capability involves porting computer geometric representations of the roadway design to the three dimensional Interactive Vehicle Model (IVM-3D) that was provided as a demonstration in the RSAS demo. Additionally, to demonstrate the full functionality of the idea, a small demonstration CAD program was created for placing New Jersey barriers on a multilane highway. The creation of this program allows the demonstration of the flow of information in the design cycle and the data dependencies involved in a drive-through capability (see figure 5.1).

Along with the creation of this demonstration drive-through capability, a review of current CAD software was conducted. Recognizing the fact that significant existing CAD and visualization capabilities have already been created, and the drive through capability should be able to import geometry representations from the wide range of CAD programs if possible. Furthermore, the intrinsic value of a drive-through capability is contingent upon the ease, speed, and accuracy of its interface with the CAD program.

### 5.1 REVIEW OF CAD PROGRAM CAPABILITIES

A range of capabilities exists to assist the highway designer in the planning and design phases of highway construction projects. Many of these are very practical computer codes for increasing the accuracy and efficiency of engineering calculations and for automating the use of survey and mapping data from computerized data bases such as the Defense Mapping Agency. Equally important are the capabilities for visualizing designs for presentation to decision makers and to get early predictions of a design's aesthetic appeal. It is not the intent of this review to discriminate among the computer codes with respect to their ability to do these tasks. However, it is important to understand how these codes are used and where a drive-through capability would enhance the design process.

Walk-through programs (there are several) are the current "state of the art" in dynamic viewing capabilities for highway construction projects. They have proven to be very valuable tools for selling construction ideas to customers as well as developing public support for projects. To date, these codes require workstations with dedicated high performance computer graphics



**Figure 5.1. Structure of the demonstration drive-through interactive vehicle model.**

“firmware” (dedicated graphics processors and memory). Additionally, they move an eyepoint through the design along a preprogrammed path and thus are not interactive.

Image quality and model resolution are two key variables that affect the time required to produce animations. If ray-traced renderings (photographic quality) are required, the animations can take days to create as all of the reflected, refracted, and specular light calculations on each surface require significant computer processing. Using the latest texturing software, high quality computer graphics can be produced in real time by mapping 2-D images on to polygons. As long as no significant three-dimensional motions about the object are required, the technique is very effective for computationally efficient visualization. Using 1991-era computer graphics workstations, graphics are limited to shaded images.

All of the CAD programs reviewed emphasize the ability to define the geometry of the design very precisely and therefore have never been very concerned with creating large numbers of polygons. Additionally the data structure is generally not constructed to enable efficient visualization. These are the issues that have typically concerned the creators of visualization software for flight simulators whose software typically has not required a great deal of precision and has taken advantage of texturing to create highly realistic, real-time animations.

One flight simulation software package is now being adapted for use in the National Advance Driving Simulator. Along with that development, they are modifying their code to create

software tools for construction of roadway visualization models consistent with roadway geometric design practices. Even more importantly, the software will define a correlated, higher resolution roadway geometry model for interaction with the vehicle dynamics model.

Thus there will be two types of CAD programs: 1) a "bottoms-up" computer code that contains all of the design detail, and 2) a "top-down" design tool will be able to define roadway geometric designs at the level of resolution required for accurate visualization and vehicle model interaction. It should be noted that some vendors of the "bottoms-up" codes do have "thinning" algorithms that reduce the number of polygons in their models. The "top-down" roadway design tool will not be available until the latter part of 1993.

## **5.2 RECOMMENDATIONS FOR DEVELOPMENT OF A DRIVE-THROUGH CAPABILITY**

There are two approaches to continued development of the drive-through capability:

- Take a high resolution CAD model created in the 'bottom-ups' mode and abstract it to something that can be rapidly rendered.
- Take a lower resolution model created in the top-down design tool and refine it only after all vehicle interaction issues have been resolved through simulation.

The first mode may be required where existing CAD data files are used as a starting point to modify some existing design. The second is the most efficient method for rapidly focusing on design issues associated with a new roadway.

- Therefore, it is recommended that a data format and interface between a CAD program (to be specified by the FHWA) and the current Interactive Vehicle Model be established.
- An interface between the Interactive Vehicle Model and the roadway design tool being developed for the National Advanced Driving Simulator should be developed.
- It is recommended that other software developments associated with National Advanced Driving Center be incorporated into the Roadway Safety Analysis System. These include the eventual roadway design tool mentioned above, and the traffic model that is being used to simulate the existence and behavior of other vehicles on the road.
- Also, in light of the fact that roadway design will require consideration of a wide range of cars as well as trucks, a standard interface should be developed that allows the vehicle dynamics model to be selected from a library of available models.



## APPENDIX A

### SURVEY OF NONLINEAR FINITE ELEMENT ANALYSIS (FEA) PROGRAMS

The purpose of this survey is to facilitate an assessment of the capabilities of nonlinear FEA codes for analysis of vehicle impacts with roadside safety structures.

#### 1. CONTACT DATA

- 1.1 Name \_\_\_\_\_
- 1.2 Title \_\_\_\_\_
- 1.3 Company \_\_\_\_\_
- 1.4 Address \_\_\_\_\_  
City, State, Zip Code \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
- 1.5 Telephone Number \_\_\_\_\_

#### 2. COMPUTER SYSTEMS TECHNOLOGIES

- 2.1 Please provide the name of all computers supported (include any special math co-processors and graphics card upgrades required)
- 2.2 Please provide name of operating systems supported.
- 2.3 Provide name of the programming language(s) in which the code is written.
- 2.4 Give benchmarks or estimates of the size and speed of problems that can be solved using the various levels of computer power- PC, Workstation, and supercomputer.
- 2.5 Describe program-to-program communication capabilities and networking protocols supported.
- 2.6 Describe post-processing capabilities (including visualization software), and systems for transfer of results to different communications media (i.e., videotape, color plotters, etc.)

#### 3. SOFTWARE TECHNOLOGIES

- 3.1 Describe the user interface features such as windows, parametric modeling, macro-programming capabilities and other symbolic input operations supported by your pre- and post-processors.
- 3.2 Describe the procedure for defining and modifying contact-impact surfaces.

- 3.3 Describe the unique features of the contact-impact algorithms in your code and any performance data that demonstrates these.
  - 3.4 Describe any unique roadside safety feature modeling elements that currently exist in your code (i.e. special guardrail, concrete median, cable, crash cushions, etc.).
  - 3.5 Describe vehicle dynamic modeling capabilities for large response angles (general rigid body motion), tire/roadway interaction force relationships, and how they are coupled mathematically to the structural dynamic models.
  - 3.6 Describe the combined geometric and material nonlinearity capability leading to the ability to analyze problems with large displacements, buckling and post-buckling, elastic-plastic and material hardening behaviors, and soil-structure interaction.
  - 3.7 Describe the unique features and limitations of the finite element formulations that are available and any data documenting their performance, and idiosyncrasies (e.g., spurious singular modes). Provide a complete description of the shell and plate elements in your code
  - 3.8 Describe the unique solvers and algorithms, (e.g. explicit, implicit, element-by-element) that are available for the nonlinear dynamic analysis of vehicle structures impacting roadside safety structures.
  - 3.9 Describe the features of automatic time incrementation, stability and analysis control for nonlinear transient dynamic analysis.
  - 3.10 Describe restart and rezoning features.
  - 3.11 What macro-element, superelement, or sub-structuring capability does your code have?
  - 3.12 Does your code have a 6 DOF non-linear spring element?
  - 3.13 Describe the capability for further program addition and modification by users. [This recognizes the existence of several levels of users with varying needs to modify and add new features to the program.]
  - 3.14 Is source code available?
4. USER-SUPPORT SERVICES
- 4.1 Describe user services and printed documentation available.
  - 4.2 Are consultant services available for tailoring the code to unique requirements?
5. FUTURE PLANS AND OTHER RELEVANT INFORMATION
- 5.1 Estimate the number users of your code (i.e., site licenses, no. of users)
  - 5.2 What are your annual revenues from sales of nonlinear FEA software?

5.3 What features/upgrades are currently under development and what is the schedule for their release?

5.4 Please provide any additional information that describes features of your code that you feel are relevant to this application.

VENDOR	RESPONSE
1. Dr. Paul Sorensen Hibbitt, Karlsson & Sorensen, Inc. 100 Medway Street Providence, RI 02906 Computer code: ABAQUS	Received
2. Mr. James Charnes President and CEO MARC Analysis Research Corp. 260 Sheridan Avenue Palo Alto, CA 94306 Computer code: MARC	Received
3. Dr. Fritz Hatt General Manager Engineering Systems International 1301 Stanley Blvd Birmingham, MI 48009 Computer code: PAM-CRASH	Received
4. Dr. Robert Taylor Vice President, Software Development Centric Engineering Systems, Inc. 3801 East Bayshore Road Palo Alto, CA 94303 Computer code: not released yet	Received
5. Dr. Jan Walczak ADINA R&D, Inc. 71 Elton Avenue Watertown, MA 02172 Compute code: ADINA	Received
6. Robert G. Whirley Methods Development Group, L-122 Lawrence Livermore National Laboratory P.O. Box 808 Livermore, CA 94550 Computer codes: NIKE3D and DYNA3D	Received
7. Tim Webster RE/SPEC Inc. 4775 Indian School Rd NE Albuquerque, NM 87110 Computer Code: SPECTROM331	Received

8. Peter Mendoza  
The MacNeal-Schwendler Corporation  
815 Colorado Blvd.  
Los Angeles CA 90041  
Computer Code: MSC/DYNA  
Not received
9. Don Whetstone  
P.O. Box 37  
Saratoga CA 95070  
Computer Code: EAL  
Not applicable
10. Jim Kennedy  
455 Frontage Rd.  
Suite 112  
Burr Ridge Ill. 60521  
Computer Code: WHAMS  
Received
11. Michael J. Murphy  
Hydrosoft International  
1595 Cross Creek Place  
Livermore CA 94550  
Computer Code: PC-DYNA  
Received
12. Mark Radamacher  
MCR Associates, Inc.  
111 W. Evelyn Avenue, Suite 301  
Sunnyvale, CA 94086  
Computer Code: ANSYS  
Received
13. Dr. John Hallquist  
LSTC  
2876 Waverly Way  
Livermore CA 94550  
Computer Code: LS/DYNA  
Received

## APPENDIX B

### INVENTORY AND IDENTIFICATION OF ISSUES CONFRONTING NEW USERS OF NONLINEAR FEA CODES

**Background.** One of the key attributes that the FHWA desires in a non-linear FEA code recommendation is an assessment of the difficulty that an experienced finite element analyst, who is not familiar with the specific code, would encounter in developing expertise in the use of the code.

**Purpose.** This exercise using two popular nonlinear FEA codes at FMC will document the impressions of two experienced structural analysts in attempting to run a small example. The two codes are ABAQUS and DYNA.

**Objectives.** It is expected that this exercise will 'flush out' most of the significant issues associated with nonlinear FEA modeling that a new user would encounter. Particularly those that an experienced user of each code would neglect due to familiarity.

**Problem Definition.** A collapsible ring device that is used in energy absorbing bridge rail systems will be modeled. The model should attempt to simulate the quasi-static crushing of the ring with a rigid plate as described in Appendix A of the CRUNCH program development and validation report. (Vol. 1, Modeling The Interaction of Heavy Vehicles With Protective Barriers).

**Procedure.** An experienced user of each code (ABAQUS and DYNA) will work with a new user of each code to build the model, run it, and produce color plots of results (animations if possible). The computer hardware and software used to accomplish each step will be documented as well as the performance of each. Each of the experienced users and the new users will have 20 hours of budgeted labor. The new users will be allowed to spend up to 20 more hours of their own time on the project but the total duration is not to exceed 1 week.

**Instructions.** Notes should be made documenting the process. These notes will serve as the results. Descriptions of the process should be as precise as possible. That is, don't say the pre-processor was frustrating, rather, point out the feature that was frustrating—such as, it was very cryptic, or didn't allow certain operations, etc. The experienced user should document the key assumptions that were made to run the problem and the things that the new user could not be expected to know that are necessary to run the problem.

Code	Personnel	
	Experienced User	New User
ABAQUS	Bill DePorter	Monica Miller
FMC-DYNA	Wing Cheng	Rob Radford



## APPENDIX C: TUTORIAL FOR THE ROADWAY SAFETY ANALYSIS SYSTEM

Instructions for running individual programs within the SCUI demonstration software -

Run SCUI demonstration software by typing in scui at the system prompt. The full path name may be required if you are not in the directory which holds the program.

Once the program is running, a main menu is displayed on the top level corner of the screen. Click the "Current Working Directory" button to set up the current working directory. Typically, the current working directory is the directory in which all data files resided, i.e., the data directory which comes with the SCUI software.

\*\*\*\*\* NOTE \*\*\*\*\*  
Make certain you set the current working directory to the directory which has all data files for the SCUI demonstration software.  
\*\*\*\*\*

### Utility Menu

- **Calculator**—display a calculator on the screen.
- **File Editor**—a screen editor whose operation is very similar to the Microsoft Word Processor. A window for file editing will appear on the screen if this menu item is selected.

Move this window to the top right corner of the screen.

Inside the file editing window, pull down the "File" menu item and select the "Open" option. Open a file called "in\_dis" which is the input query file for the XYPLOT program.

- **XYPLOT**—a FMC developed XY plot animation program.

A window appears on the screen if this menu item is selected.

Click the "Run" button to activate the XYPLOT program. The XYPLOT always appears on the lower left corner. You can change the title of the plot by modifying the input query file in file editing window and then save the file. The change will be effective in the next plot cycle. Put the cursor inside the plotting window and press H key until you see help window pops up.

- **Network**—a graphical demonstration program to show the distributed computing scenario. Select the scenario by clicking the mouse on the item you want.
- **Done**—exit this program
- **Clock**—display a clock on the screen
- **Set Working Directory**—change the current working directory
- **Exit**—exit the SCUI demonstration software

## Handling Menu

- **Interactive Vehicle Model**—a FMC developed interactive wheel vehicle model simulation. If this item is selected, a dynamics program and a graphics program are activated simultaneously. The following are the responses to the questions for the graphics program. Select:

- Interactive simulation mode
- Pickup Truck for suspension model (type in 1)
- Pickup Truck for geometric model (type in 1)
- Flat\_terrain.dat for the terrain (type in 1)

If you intend to use the geometry file which is created by the N.J. Barrier Placement Program, then type in 0.

Next enter two file names, separated by a space, on the provided area. The first name is always "flat\_terrain.dat", and the second file name is the name of the geometry file.

Now you should see the simulation window and x-y plot window. Pull down the I/O menu and select "set vehicle speed" and enter an initial speed.

Pulldown the I/O menu and select "Connect to IVM3D" to set up the communication between the dynamics and graphics programs. As soon as the linkage is established, a pop-up window appears on the screen to show the version number of both programs. Select the "DONE" button to start the simulation.

**Vehicle control**—The user can control the vehicle using either the spaceball or the numeric key pad on the right hand side of the keyboard. If the spaceball is used, press spaceball key 1 to control the speed of the vehicle. Push the ball forward, the speed of the vehicle increases. Pull the ball backward, the speed of the vehicle decreases.

The spaceball key 2 is for steering the vehicle. Twist the ball to left, the vehicle turns left and twist the ball to right, the vehicle turns right.

For the numeric keypad, key 8 is for increasing the speed, key 2 is for reducing the speed, key 4 is for left turn, and key 6 is for right turn.

There is a dial on the simulation window to indicate the speed (number on the right hand side of the dial) and the steering angle (number on the top side of the dial).

**XYPLOT control**—pull down I/O menu and select "Time History", and select an item from the pop-up menu. The vertical scale of the x-y plot can be adjusted by placing the cursor on top of angle button (on the left hand side of the window) and click the left mouse button.

**Window control**—pull down Windows menu and select "Camera No. 1" for driver's view and "World+Camera No. 1" for both world and driver's views. Do not select camera number 2.

**Exit**—pull down the I/O menu and select the exit item to quit this simulation session.

Do not select any items under the "Record" pull down menu.

- **Animation (DAVIS)**—FMC developed Dynamic Analysis VISualization

**Software.** Select the "Run" button in the pop-up window to activate the program. Once the graphics is displayed on the screen, pull down I/O menu and select the "Start Animation" item to start the animation.

Pull down I/O menu and select "Read 2nd Simulation File" for comparing two simulations. The file name for the second simulation is called 410.anm.

Pull down I/O menu and select "Read setup file" to set the predefined viewing parameters. The file name for the set-up file is called 4bump.setup.

For x-y plot, pull down "Time History" menu and select rigid".

**Exit**—pull down the I/O menu and select the exit item to quit this animation session.

Do not select any items under the "Record" pull down menu.

- **Pre-processors (N.J. Barrier Placement Program)**—a FMC developed graphics program for interactively placing highway barriers on the roadway.

Once this option is selected, the whole screen is covered with two windows. The window on the left side of the screen is the display window which displays the road surface and the other objects. The window on the right side of the screen is the menu window in which the user can interact with the program.

Within the menu window, there are five sub-windows. The function of these sub-windows are:

- TRANSLATION & ROTATION sub-window is for changing the eye location for viewing the objects in the display window.

- PROJECTION sub-window is for changing the projection mode (perspective or orthographic) in the display window.

The ORTHO/PERSPECTIVE button is used to toggle the current projection mode.

- FILE subwindow is for saving all geometric information into a file and/or exit the program.

The geometry file saved from this program can be used as an input for the Interactive Vehicle Model. While running the Interactive Vehicle Model, when program asks for the terrain information, the user should type in 0 and then 2 file names on the provided space. The 2 file names should be separated by a space. The first file name is always "flat\_terrain.dat" and the second file name is the name of the geometry file.

- BARRIER sub-window is for adding or deleting barriers. There are 6 buttons in this window, namely ADD, DELETE, ROTATE, ADD 2 PTS, DEG and MOVE. If the button is high-lighted, this means that button is active. The active button can be deactivated by clicking on that button again.

ADD button is for adding new barrier to the roadway. Once this button is selected, the user can place a new barrier on the roadway by moving the cursor to the desired location in the display window and then clicking the left mouse button. The newly added barrier is high-lighted with red boundary line.

This high-lighted red boundary line barrier is the current active barrier.

DELETE button is for deleting the current active barrier. The user can select any existing barrier as the current active barrier by placing the cursor on top of the barrier and then click the left mouse button.

ROTATE button is for rotating the current active barrier. The user can change the orientation of the current active barrier by pressing the left mouse button and dragging across the screen until it reaches to the desired orientation, then the user can release the left mouse button. For information purpose, the angle of rotation is echoed on the right hand side of the ROTATE button.

ADD 2 PTS button is for clicking left mouse on 1st point, then clicking second point. System will create line barrier for you.

MOVE button is for changing the location of the current active barrier. The operation of this button is very similar to the ROTATE button.

- TRAFFIC LANES sub-window is for generating number of lanes on the roadway. When the CREATE button is selected by clicking the left mouse button, the program will ask how many lanes to be created. The default value is 4.

Once the user entered the desired number, the display window displays the roadway with the same number of lanes.

## FEA Menu

- **Analysis (DYNA3D)**—execute the DYNA3D program. If this menu item is selected, a window appears on the screen to ask for all the file names for the DYNA3D run. After inputting all the names, click the "Run" to initiate the run. A log file is created which saves the screen output to a file for later reference.
- **Analysis (NIKE3D)**—execute the NIKE3D program. If this menu item is selected, a window appears on the screen to ask for all the file names for the NIKE3D run. After inputting all the names, click the "Run" to initiate the run. A log file is created which saves the screen output to a file for later reference.
- **Pre-processors (INGRID)**—execute the INGRID program. If this menu item is selected, a window appears on the screen to ask for all the file names for the INGRID run. After inputting all the names, click the "Run" to initiate the run. A log file is created which saves the screen output to a file for later reference. When the program is running, the following is the responses to the questions.
  - Overwrite the File [y/n]: (type in y)
  - Select a graphics device > (type in 1)
  - type in draw for drawing the picture

- type in exit to terminate the program
- **Post-processors (TAURUS)**—execute the TAURUS program. If this menu item is selected, a window appears on the screen to ask for all the file names for the TAURUS run. After inputting all the names, click the "Run" to initiate the run. A log file is created which saves the screen output to a file for later reference. When the program is running, the following is a list to draw a picture.
  - state 50 (select time step 50)
  - rx 45 (rotate x 45 deg)
  - ry -45 (rotate y -45 deg)
  - fringe 9 (draw the contour)
  - type in exit to terminate the program
- **Post-processors (POSTFEA)**—a FMC developed stress animation Software. Select the "Run" button in the pop-up window to activate the program. Once the graphics is displayed on the screen, pull down I/O menu and select the "Start Animation" item to start the animation.

Pull down Stress menu and select "Element Boundary" to turn the display of element boundary.

Pull down Display menu and select "Halt" to temporary halt the animation, select the "Resume" to resume the animation.

Pull down Stress menu and select "Select Stress type" to select different type of stress.

Exit—pull down the I/O menu and select the exit item to quit this animation session.

Do not select any items under the "Record" pull down menu.

## CAD Menu

Nothing available now.

## TestData Menu

- **Percent Error**—a FMC developed percent error program. The user can activate this program by selecting this menu item. The following is list of steps to run this program.
  - type in 1 (for select signal pairs)
  - type in 2 (for enter active signal pair source filenames)
  - type in 1 (for interactive input)
  - type in per1.dat (filename for input #1)
  - type in y (for plotting the data)
  - type in n (for saving a plot file)
  - type in per2.dat (filename for input #2)
  - type in y (for plotting the data)
  - type in n (for saving a plot file)
  - type in n (for saving a plot file)
  - type in 7 (for return to previous menu)
  - type in 6 (for comparing signals)
  - type in 2 (for display multiple signal pair percent error)

- etc
- select return to previous menu until you can exit the program
- **Data Filtering**—a FMC developed data filtering program. The user can activate this program by selecting this menu item. The following is list of steps to run this program.
  - type in 1 (for select and read input data files)
  - type in 1 (for input file no)
  - type in per1.dat (filename for input #1)
  - type in y (for more data file)
  - type in 2 (for input file no)
  - type in per2.dat (filename for input #2)
  - type in n (for more data file)
  - type in 10 (for filtering the data)
  - select whatever the option you want like to do
  - etc
  - select return to previous menu until you can exit the program.

### **Design Menu**

Nothing available now.

### **Help Menu**

Nothing available now.

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